$\mathcal{A}_{\rm CP}$ Puzzle : Possible Evidence for Large Strong Phase in $B \to K\pi$ Color-Suppressed Tree Amplitude

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In QCD Factorization(QCDF), the suppression of the color-suppressed tree amplitude relative to the color-allowed one in $B \to K\pi$ decay implies a direct CP asymmetry in $B^- \to K^-\pi^0$ to be of the same sign and comparable in magnitude to that in $\bar{B}^0 \to K^+\pi^-$, in contradiction with experiment. This is the $A_{\rm CP}$ $B \to K\pi$ puzzle. One of the current proposal to solve this puzzle is the existence of a large color-suppressed amplitude with large strong phase which implies also a large negative $\bar{B}^0 \to \bar{K}^0\pi^0$ CP asymmetry. In this paper, by an essentially model-independent calculation, we show clearly that the large negative direct CP asymmetry in $\bar{B}^0 \to \bar{K}^0\pi^0$ implies a large C/T, the ratio of the color-suppressed to the color-allowed tree amplitude and a large negative strong phase for C. By adding to the QCDF amplitude an additional color-suppressed term to generate a large C/T and a large strong phase for C and an additional penguin-like contribution, we obtain branching ratios for all $B \to K\pi$ modes and CP asymmetry for $\bar{B}^0 \to K^+\pi^-$ and $B^- \to K^-\pi^0$ in agreement with experiment, and a large and negative CP asymmetry in $\bar{B}^0 \to \bar{K}^0\pi^0$ which could be checked with more precise measurements.

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I. INTRODUCTION

In the penguin-dominated $B \to K\pi$ decays, the color-suppressed tree contribution(C) is suppressed relative to the color-allowed tree contribution(T) because of the small Wilson coefficient a_2 relative to a_1. One would then expect the direct CP asymmetries in $B^- \to K^-\pi^0$ and $\bar{B}^0 \to K^-\pi^+$ to be essentially given by the color-allowed tree and strong penguin interference terms(TP). The CP asymmetry($\mathcal{A}_{\rm CP}$) in $B^- \to K^-\pi^0$ would be of the same sign and comparable in magnitude to that in $\bar{B}^0 \to K^-\pi^+$. The current measurements[1], though with large errors, seem to indicate a positive CP asymmetry for $B^- \to K^-\pi^0$, in opposite sign to the negative $\bar{B}^0 \to K^-\pi^+$ CP asymmetry measured with greater accuracy. This is the $A_{\rm CP}$ puzzle[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12].

To reverse the sign of the predicted $B^- \to K^-\pi^0$ CP asymmetry, one would need a large color-suppressed tree terms, i.e a large C/T ratio, and also a large strong phase for C, as will be shown in the following. Since the color-suppressed tree-penguin interference term in $B^- \to K^-\pi^0$ is opposite in sign to that in $\bar{B}^0 \to \bar{K}^0\pi^0$, the $\bar{B}^0 \to \bar{K}^0\pi^0$ CP asymmetry would become large and negative. If the positive asymmetry for $B^- \to K^-\pi^0$ and a large negative $\bar{B}^0 \to \bar{K}^0\pi^0$ CP asymmetry are confirmed by new measurements, this would be a clear evidence for the enhanced color-suppressed tree contribution to CP asymmetries in $B \to K\pi$ decays. Apart from the possibility of new physics[7, 8, 13] to solve the $A_{\rm CP}$ $B \to K\pi$ puzzle, recent calculations in the standard model(SM), as done in perturbative QCD (pQCD)[2, 5], in QCD Factorization(QCDF) with large hard scattering corrections[14] seem to obtain a large color-suppressed enhancement in $B \to \pi\pi$ and $B \to K\pi$ decays. The calculation in [8] also shows that the color-suppressed tree contribution has to be large to solve the $B \to K\pi$ $A_{\rm CP}$ puzzle within the standard model. Various phenomenological analyses[15] using $SU(3)$ symmetry obtain also a large C/T ratio. Final state interaction (FSI) rescattering term with a large absorptive part, like the charmed meson rescattering charming penguin contribution[16, 17, 18, 19, 20, 21, 22], could also produce a large C/T with a strong phase[3, 22, 23, 24], for example, through the CKM-suppressed, color-allowed tree rescattering $B \to K^*\rho \to K\pi$ process, which produces a tree-penguin interference term responsible for CP asymmetry, similar to the process $B \to \rho\rho \to \pi\pi$ in $B \to \pi\pi$ decays. Before going further in analyzing these possibilities, one would like to have a model-independent calculation to show that, apart from the possibility of new physics, the solution to the $A_{\rm CP}$ puzzle is an enhanced color-suppressed contribution to CP asymmetry in $B \to K\pi$ decays. In the next section we will show in an essentially model-independent calculation that the large negative $\bar{B}^0 \to \bar{K}^0\pi^0$ CP asymmetry requires a large ratio C/T with C mainly absorptive. We then show that with this additional contribution to the color-suppressed tree term and a penguin-like additional term as given in [25] , QCDF could predict all the branching ratios and CP asymmetries for $B \to K\pi$ decays consistent with experiment.

II. MODEL-INDEPENDENT DETERMINATION OF STRONG PHASES IN $B \to K\pi$

As our analysis is based on QCD Factorization, for convenience, we reproduce here the QCDF $B \to K\pi$ decay

amplitudes given in [25]. We have[26, 27, 28, 29] :

$$A(B^- \to K^-\pi^0) = -i\frac{G_F}{2} f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$$
$$(V_{ub}V_{us}^* a_1 + (V_{ub}V_{us}^* + V_{cb}V_{cs}^*)[a_4 + a_{10} + (a_6 + a_8)r_\chi])$$
$$-i\frac{G_F}{2} f_\pi F_0^{BK}(m_\pi^2)(m_B^2 - m_K^2)$$
$$\times\left(V_{ub}V_{us}^* a_2 + (V_{ub}V_{us}^* + V_{cb}V_{cs}^*) \times \frac{3}{2}(a_9 - a_7)\right)$$
$$-i\frac{G_F}{2} f_B f_K f_\pi$$
$$\times [V_{ub}V_{us}^* b_2 + (V_{ub}V_{us}^* + V_{cb}V_{cs}^*) \times (b_3 + b_3^{ew})] \quad (1)$$

$$A(B^- \to \bar{K}^0\pi^-) = -i\frac{G_F}{\sqrt{2}} f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$$
$$+(V_{ub}V_{us}^* + V_{cb}V_{cs}^*)\left[a_4 - \frac{1}{2}a_{10} + (a_6 - \frac{1}{2}a_8)r_\chi\right]$$
$$-i\frac{G_F}{\sqrt{2}} f_B f_K f_\pi$$
$$\times [V_{ub}V_{us}^* b_2 + (V_{ub}V_{us}^* + V_{cb}V_{cs}^*) \times (b_3 + b_3^{ew})] \quad (2)$$

and for $\bar{B}^0$:

$$A(\bar{B}^0 \to K^-\pi^+) = -i\frac{G_F}{\sqrt{2}} f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$$
$$\left(V_{ub}V_{us}^* a_1 + (V_{ub}V_{us}^* + V_{cb}V_{cs}^*)[a_4 + a_{10} + (a_6 + a_8)r_\chi]\right)$$
$$-i\frac{G_F}{\sqrt{2}} f_B f_K f_\pi \left[(V_{ub}V_{us}^* + V_{cb}V_{cs}^*) \times (b_3 - \frac{b_3^{ew}}{2})\right] \quad (3)$$

$$A(\bar{B}^0 \to \bar{K}^0\pi^0) = i\frac{G_F}{2} f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$$
$$\times(V_{ub}V_{us}^* + V_{cb}V_{cs}^*)\left[a_4 - \frac{1}{2}a_{10} + (a_6 - \frac{1}{2}a_8)r_\chi\right]$$
$$-i\frac{G_F}{2} f_\pi F_0^{BK}(m_\pi^2)(m_B^2 - m_K^2)$$
$$\left(V_{ub}V_{us}^* a_2 + (V_{ub}V_{us}^* + V_{cb}V_{cs}^*) \times \frac{3}{2}(a_9 - a_7)\right)$$
$$+i\frac{G_F}{2} f_B f_K f_\pi \left[(V_{ub}V_{us}^* + V_{cb}V_{cs}^*) \times (b_3 - \frac{b_3^{ew}}{2})\right] \quad (4)$$

where $r_\chi = \frac{2m_K^2}{(m_b - m_d)(m_d + m_s)}$ is the chirally-enhanced terms in the penguin O_6 matrix element. The annihilation term b_i are evaluated with the factor $f_B f_{M_1} f_{M_2}$ included and normalized relative to the factor $f_K F_0^{B\pi}(m_B^2 - m_\pi^2)$ in the factorisable terms. For the $B^- \to \pi^-\pi^0$ amplitude, we have:

$$A(B^- \to \pi^-\pi^0) = -i\frac{G_F}{2} f_\pi F_0^{B\pi}(m_\pi^2)(m_B^2 - m_\pi^2)$$
$$\Big(V_{ub}V_{ud}^*(a_1 + a_2) + (V_{ub}V_{ud}^* + V_{cb}V_{cd}^*)$$
$$\times\frac{3}{2}(a_9 - a_7 + a_{10} + a_8 r_\chi)\Big) \quad (5)$$

We see that the $B \to K\pi$ decay amplitudes consist of a QCD penguin(P) $a_4 + a_6 r_\chi$, a color-allowed tree(T) a_1, a color-suppressed tree(C) a_2 , a color-allowed electroweak penguin(EW) $a_9 - a_7$, a color-suppressed electroweak penguin(EWC) $a_{10} + a_8 r_\chi$ terms. (There are also the penguin contribution given by $a_4^u + a_6^u r_\chi$ term not shown in the above expressions, for simplicity). Because of the relative large Wilson coefficients, the QCD penguin, the color-allowed tree and the color-allowed electroweak contribution are the major contributions in $B \to K\pi$ decays. The $B \to K\pi$ amplitude in Eqs.(1)-(4) are then given as the sum of the allowed-tree T, the color-suppressed tree C, the color-allowed electroweak penguin $P_{\rm W}$, the color-suppressed electroweak penguin, $P_{\rm WC}$, tree-annihilation A (the b_2 terms in Eq.(1)-(2)) the penguin-induced weak annihilation $P_{\rm A}$. One can further simplify the expressions, by grouping together the penguin and penguin weak annihilation as an effective penguin $P_{\rm eff}$ as usually done[28], furthermore, since the CKM-suppressed, color-suppressed b_2 terms are much smaller than the color-allowed tree term, we could also neglect A, and put the tree terms and the CKM-suppressed part of P and P_A into an effective $T_{\rm eff}$ and $C_{\rm eff}$. The $B \to K\pi$ amplitudes in terms of the effective penguin and tree amplitude are then (putting $P_{\rm eff} = P$, $T_{\rm eff} = T$, $C_{\rm eff} = C$), we have (in the notations of Ref.[14]):

$$\begin{aligned}
A(B^- \to K^-\pi^0) &= \frac{1}{\sqrt{2}}(Pe^{i\delta_P} + Te^{i\delta_T}e^{i\gamma} + Ce^{i\delta_C}e^{-i\gamma} \\
&+ P_{\rm W} + \frac{2}{3}P_{\rm WC}), \\
A(B^- \to \bar{K}^0\pi^-) &= Pe^{i\delta_P} - \frac{1}{3}P_{\rm WC}, \\
A(\bar{B}^0 \to K^-\pi^+) &= Pe^{i\delta_P} + Te^{i\delta_T}e^{-i\gamma} + \frac{2}{3}P_{\rm WC}, \\
A(\bar{B}^0 \to \bar{K}^0\pi^0) &= -\frac{1}{\sqrt{2}}(Pe^{i\delta_P} - Ce^{i\delta_C}e^{-i\gamma} \\
&- P_{\rm W} - \frac{1}{3}P_{\rm WC}). \qquad (6)
\end{aligned}$$

with the strong phase $\delta_P, \delta_T, \delta_C$ for the penguin, color-allowed and color-suppressed tree, respectively and the weak phase γ of the CKM matrix element V_{ub} is written explicitly in the color-allowed T and color-suppressed C terms. In terms of the relative strong phase δ_{PT}, δ_{CT}, and to take into account of the fact that the real part of the penguin amplitude P is negative in QCDF, we have $\delta_P = \delta_{PT} + \pi + \delta_T$, and $\delta_C = \delta_{CT} + \delta_T$.

Consider now the CP-averaged $\Gamma_{\rm av}$and CP-difference $\Gamma_{\rm as}$ for $B \to K\pi$ decay rates are then, with $\Gamma_{\rm av} = (\Gamma(B \to K\pi) + \bar{\Gamma}(B \to K\pi))/2$, $\Gamma_{\rm as} = (\Gamma(B \to K\pi) - \bar{\Gamma}(B \to K\pi))$ and $\Gamma(B \to K\pi)$ and $\bar{\Gamma}(B \to K\pi)$ denotes the decay rate for the corresponding charge-conjugate

mode. We have

$$\Gamma_{\rm av}(B^- \to K^-\pi^0) = \frac{P^2}{2} - P\,T\cos(\delta_{PT})\,\cos(\gamma)$$
$$-P\,C\cos(\delta_{PT}-\delta_{CT})\,\cos(\gamma) + T\,C\cos(\delta_{CT})$$
$$-P\,P_W\cos(\delta_{PT}+\delta_T)\,\cos(\gamma) + T\,P_W\cos(\delta_T)\,\cos(\gamma)$$
$$+C\,P_W\cos(\delta_{CT}+\delta_T)\,\cos(\gamma) + \frac{T^2}{2} + \frac{C^2}{2} + \frac{P_W^2}{2} \quad (7)$$
$$\Gamma_{\rm av}(B^- \to \bar{K}^0\pi^-) = P^2 \quad (8)$$
$$\Gamma_{\rm av}(\bar{B}^0 \to K^-\pi^+) = P^2 - 2\,P\,T\cos(\delta_{PT})\,\cos(\gamma) + +T^2 \quad (9)$$
$$\Gamma_{\rm av}(\bar{B}^0 \to \bar{K}^0\pi^0) = \frac{P^2}{2} + P\,C\cos(\delta_{PT}-\delta_{CT})\,\cos(\gamma)$$
$$+P\,P_W\cos(\delta_{PT}+\delta_T)\,\cos(\gamma)$$
$$+C\,P_W\cos(\delta_{CT}+\delta_T)\,\cos(\gamma) + \frac{C^2}{2} + \frac{P_W^2}{2} \quad (10)$$

where P, T, C and P_W are positive and the negative real part of the penguin term has been taken into account in the phase $\delta_P = \pi + \delta_{PT} + \delta_T$ as mentioned above. Also, to simplify the analysis, we have neglected the color-suppressed electroweak penguin P_{WC} contribution which is smaller than the color-allowed elctroweak penguin P_W by an order of magnitude as can be seen from the a_8 and a_{10} terms in Eqs.(1)-(4). For the CP-difference decay rates, we obtain:

$$\Gamma_{\rm as}(B^- \to K^-\pi^0) = 2\,P\,T\sin(\delta_{PT})\,\sin(\gamma)$$
$$+2\,P\,C\sin(\delta_{PT}-\delta_{CT})\,\sin(\gamma) + 2\,T\,P_W\sin(\delta_T)\,\sin(\gamma)$$
$$+2\,C\,P_W\sin(\delta_{CT}+\delta_T)\,\sin(\gamma)\ , \quad (11)$$
$$\Gamma_{\rm as}(B^- \to \bar{K}^0\pi^-) = 0\ , \quad (12)$$
$$\Gamma_{\rm as}(\bar{B}^0 \to K^-\pi^+) = 4\,P\,T\sin(\delta_{PT})\,\sin(\gamma)\quad , \quad (13)$$
$$\Gamma_{\rm as}(\bar{B}^0 \to \bar{K}^0\pi^0) = -2\,P\,C\sin(\delta_{PT}-\delta_{CT})\,\sin(\gamma)$$
$$+2\,C\,P_W\sin(\delta_{CT}+\delta_T)\,\sin(\gamma)(14)$$

and the CP asymmetries are then given by:

$$\mathcal{A}_{\rm CP}(B \to K\pi) = \frac{\Gamma_{\rm as}(B \to K\pi)}{2\Gamma_{\rm av}(B \to K\pi)} \quad (15)$$

As the $B \to K\pi$ branching ratios have been measured with an accuracy at the 10^{-6} level, it is possible to use the differences in the measured branching ratios and CP asymmetry to determine the relative T/P, C/T and the strong phase δ_{PT}, δ_{CT}, as done for $B \to \pi\pi$ decays[24, 30] in which the relative strong phase δ_{PT} can be extracted from the measured mixing-induced and direct CP asymmetry parameters $S_{\pi^+\pi^-}$ and $C_{\pi^+\pi^-}$. For example, by neglecting the $(P/T)^2$ term in $S_{\pi^+\pi^-}$, one would obtain:

$$\tan\delta_{PT} \approx -C_{\pi^+\pi^-}/S_{\pi^+\pi^-} \quad (16)$$

which gives, for $\bar{B}^0 \to \pi^-\pi^+$), $\delta_{PT} = -36.5^\circ$ close to the value -41.3° in a more precise determination [24]. Similar determination of the strong phase could be done for $B \to K\pi$ decays by using the quantity $D = 2(\Gamma_{\rm av}(\bar{B}^0 \to K^-\pi^+) - \Gamma_{\rm av}(B^- \to \bar{K}^0\pi^-) - T^2)$ which is given by:

$$D = -4\,PT\cos(\delta_{PT})\,\cos(\gamma) \quad (17)$$

The ratio $R_{K^-\pi^+} = \Gamma_{\rm as}(\bar{B}^0 \to K^-\pi^+)/D$ is then:

$$R_{K^-\pi^+} = -\tan(\delta_{PT})\tan(\gamma) \quad (18)$$

from which we obtain :

$$\tan(\delta_{PT}) = -\frac{R_{K^-\pi^+}}{\tan(\gamma)}\quad ,$$
$$\sin(\delta_{PT}) = -\frac{R_{K^-\pi^+}}{\sqrt{(}\tan^2(\gamma) + R^2_{K^-\pi^+})} \quad (19)$$

From the measured $B \to K\pi$ branching ratios and the QCDF expression for T^2, we obtain $D = -5.35$, $R_{K^-\pi^+} = 0.71$ (in terms of the branching ratios and in unit of 10^{-6}) which give,

$$\tan(\delta_{PT}) = -0.30, \quad \delta_{PT} = -17^\circ. \quad (20)$$

within an error of $20-30\%$, including a small theoretical uncertainty in the use of QCDF for T^2 which makes only a small contribution to D relative to the main tree-penguin interference term. This value is smaller than the value -36.5° for δ_{PT} in $\bar{B}^0 \to \pi^-\pi^+$ mentioned above, but the small value of the strong phase δ_{PT} we obtained here from $\bar{B}^0 \to K^-\pi^+$ could be due to the cancellation between the factorisable term, penguin-induced weak annihilation and FSI charmed meson intermediate states contribution to produce a negative CP asymmetry in $\bar{B}^0 \to K^-\pi^+$) decay[25].

We now come to the $\mathcal{A}_{\rm CP}$ puzzle. As mentioned earlier, the solution of the puzzle requires a moderate C/T ratio, but with a strong phase δ_{CT} sufficiently large to keep the real part of the color-suppressed tree contribution close to QCDF prediction, like those computed for $B \to \pi\pi$ decays[31]. Then the large absorptive part could find an explanation from FSI effects as mentioned earlier. Indeed, as shown in the following, such a large strong phase for C is required to produce a large CP asymmetry for $\bar{B}^0 \to \bar{K}^0\pi^0$. Defining $R_{\bar{K}^0\pi^0} = \Gamma_{\rm as}(\bar{B}^0 \to \bar{K}^0\pi^0)/D$, we have:

$$R_{\bar{K}^0\pi^0} = -\frac{1}{2}\frac{C}{T}\Big(\sin(\delta_{CT})\,\tan(\gamma) + \cos(\delta_{CT})R_{K^-\pi^+}$$
$$+R_W\sin(\delta_{CT}+\delta_T)\sqrt{(}R^2_{K^-\pi^+} + \tan^2(\gamma))\Big) \quad (21)$$

where $R_W = P_W/P$ which is given approximately by QCDF[28]:

$$R_W = \frac{3}{2}\frac{f_\pi F^{BK}(0)}{f_K F^{B\pi}(0)}\frac{|a_9 - a_7|}{|a_4 + a_6 r_\chi|} \approx 0.13 \quad (22)$$

The CP asymmetry for $\bar{B}^0 \to \bar{K}^0\pi^0$ is then

$$\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0) = \frac{D\,R_{\bar{K}^0\pi^0}}{2\,\mathcal{B}(\bar{B}^0 \to \bar{K}^0\pi^0)} \quad (23)$$

with D given in terms of the CP-averaged $B \to K\pi$ branching ratios, experimentally, $D = -5.35$, as mentioned above (in unit of 10^{-6}).

A nice feature of the above expression for $R_{\bar{K}^0\pi^0}$ is that it gives the CP asymmetry for $\bar{B}^0 \to \bar{K}^0\pi^0$ in terms of the strong phase δ_{CT}, the measured $\bar{B}^0 \to K^-\pi^+$ CP asymmetry and the weak phase γ . For a large strong phase δ_{CT}, the $\cos(\delta_{CT})R_{K^-\pi^+}$ term is suppressed so that the dependence of $R_{\bar{K}^0\pi^0}$ on $R_{K^-\pi^+}$ is weak. There is also some dependence on δ_T in the electroweak contribution to $R_{\bar{K}^0\pi^0}$ which could produce a small uncertainty on the CP asymmetry, about $10-15\%$, roughly the size of the electroweak penguin contribution. Thus the CP asymmetry for $\bar{B}^0 \to \bar{K}^0\pi^0$ depends essentially on the strong phase of the color-suppressed tree contribution δ_{CT}.

Numerically, from the measured $\mathcal{B}(\bar{B}^0 \to K^-\pi^+)$, the CP asymmetry $\mathcal{A}_{\rm CP}(\bar{B}^0 \to K^-\pi^+)$, $\gamma = 67^\circ$, and taking $\delta_T = 30^\circ$, we obtain:

$$\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0)=0.27\frac{C}{T}\left[1.31\sin(\delta_{CT})+ 0.44\cos(\delta_{CT})\right] \tag{24}$$

Thus a large negative value for δ_{CT} could produce a large negative $\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0)$ which is needed to accommodate the measured positive asymmetry for $(B^- \to K^-\pi^0)$[1]. For example, with $\delta_{CT} = -72^\circ$, one would get $\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0) = -0.30(C/T)$ which implies $C/T = 1/2$ for $\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0) = -0.15$. If we neglect the electroweak penguin P_W term, we would have:

$$\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0)=0.27\frac{C}{T}\left[1.17\sin(\delta_{CT})+ 0.35\cos(\delta_{CT})\right] \tag{25}$$

independent of δ_T. The same value for the CP asymmetry would implies $\delta_{CT} = -75^\circ$, close to the value obtained with electroweak penguin. Thus the determination of C/T will not be greatly affected by the electroweak penguin contribution. In general from QCDF one expects a small δ_T , in our calculation we will put $\delta_T = 30^\circ$. In terms of the measured $\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0)$, from Eq.(23), C/T is then:

$$(\frac{C}{T}) = \frac{\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0)}{0.27\left[1.31\sin(\delta_{CT}) + 0.44\cos(\delta_{CT})\right]} \tag{26}$$

As shown in Fig.1, for the strong phase in the range $-(50^\circ - 70^\circ)$, C/T is of the order $0.3 - 0.4$ for an asymmetry of -0.10, with a larger asymmetry of -0.15 , C/T become larger, of the order $0.5 - 0.6$. Thus in an essentially model-independent calculation, we have shown that a large and negative $\bar{B}^0 \to \bar{K}^0\pi^0$ CP asymmetry, which is required to produce a sizable positive CP asymmetries in $B^- \to K^-\pi^0$, implies a large color-suppressed tree C term and its strong phase in $B \to K\pi$ decay, with a ratio C/T of the order $0.4 - 0.6$ and the strong phase δ_{CT} in the range $-(50-70)^\circ$. Indeed, a recent analysis in QCDF shows that the $A_{\rm CP}$ $B \to K\pi$ puzzle could be solved with a color-suppressed tree a_2 term large and having a large negative strong phase[14]. In the next section, we will show that, by adding to the QCDF amplitude, an additional color-suppressed tree contribution with this size to reverse the sign of the $B^- \to K^-\pi^0$ asymmetry, together with the additional penguin terms (charming penguin etc.)[25], indeed good agreement with experiment is obtained for all the $B \to K\pi$ branching ratios and CP asymmetries.

III. $B \to K\pi$ DECAYS IN QCDF WITH ADDITIONAL PENGUIN AND COLOR-SUPPRESSED CONTRIBUTIONS

In a previous paper[25], we have shown that the $B \to K\pi$ branching ratios and the $\bar{B}^0 \to K^+\pi^-$ CP asymmetry could be described by QCDF with a mainly absorptive additional penguin terms (charming penguin etc.), with a strength 30% of the penguin term. However the predicted CP asymmetry for $B^- \to K^-\pi^0$ is of the same sign and magnitude to that for $\bar{B}^0 \to K^-\pi^+$, in disagreement with the measured value. Therefore, to reverse the sign of the predicted asymmetry, we need a large negative $\bar{B}^0 \to \bar{K}^0\pi^0$ asymmetry and hence a color-suppressed tree term with large magnitude and large negative strong phase. By adding this term to the QCDF $B \to K\pi$ amplitudes given in our previous work[25] one would obtain correct predictions for $B \to K\pi$ branching ratios and CP asymmetries as will be shown below.

With the same hadronic, CKM parameters and the additional penguin term δP given in [25], and writing the color-suppressed additional term as $\delta C = ra_2(k_1 + i\,k_2)$ where ra_2 is the real part of a_2, and taking $k_1 = 0$, $k_2 = -1.7$, the computed branching ratios and direct CP asymmetries, with $\rho_H = 1, \phi_H = 0$ and $\phi_A = -55^\circ$ as in scenario S4 of [28] are shown in Fig.2 and Fig.3 as function of ρ_A. For convenience we also give in Table I and Table II the computed values at $\rho_A = 1$ as in S4 with and without the additional penguin-like δP and color-suppressed δC contribution. We see that with these additional contributions, all the branching ratios and CP asymmetries are in good agreement with the measured values. In particular, the $\bar{B}^0 \to \bar{K}^0\pi^0$ branching ratio is slightly larger than the previous predicted value of 8.9×10^{-6} due to the additional δC contribution and is closer to experiment, while other predicted branching ratios remain practically unchanged.

In our previous work[25], we give predictions for the $\bar{B}^0 \to \bar{K}^0\pi^0$, $B^- \to K^-\pi^0$ and $\bar{B}^0 \to K^-\pi^+$ branching ratios in terms of the computed differences $2\mathcal{B}(\bar{B}^0 \to \bar{K}^0\pi^0) - r_b\mathcal{B}(B^- \to \bar{K}^0\pi^-)$, $2\,r_b\mathcal{B}(B^- \to K^-\pi^0) - \mathcal{B}(\bar{B}^0 \to K^-\pi^+)$, $\mathcal{B}(\bar{B}^0 \to K^-\pi^+) - r_b\mathcal{B}(B^- \to \bar{K}^0\pi^-)$ and the measured $\bar{B}^0 \to K^-\pi^+$ and $B^- \to \bar{K}^0\pi^-$ branching ratios. The good agreement with experiment

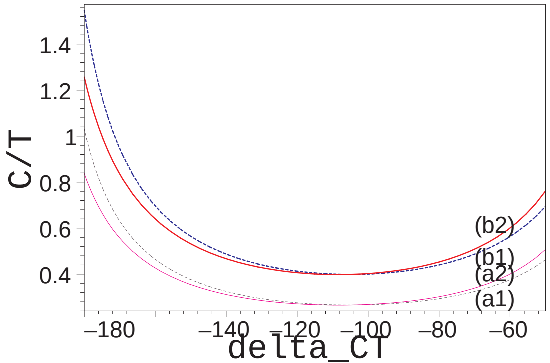

FIG. 1: The ratio C/T plotted against δ_{CT}, the strong phase of the color-suppressed tree contribution C . (a1,a2) are the curves for $\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0) = -0.10$ with δ_T taken to be 0.0 and 30°, respectively, (b1,b2) are similar curves for $\mathcal{A}_{\rm CP}(\bar{B}^0 \to \bar{K}^0\pi^0) = -0.15$.

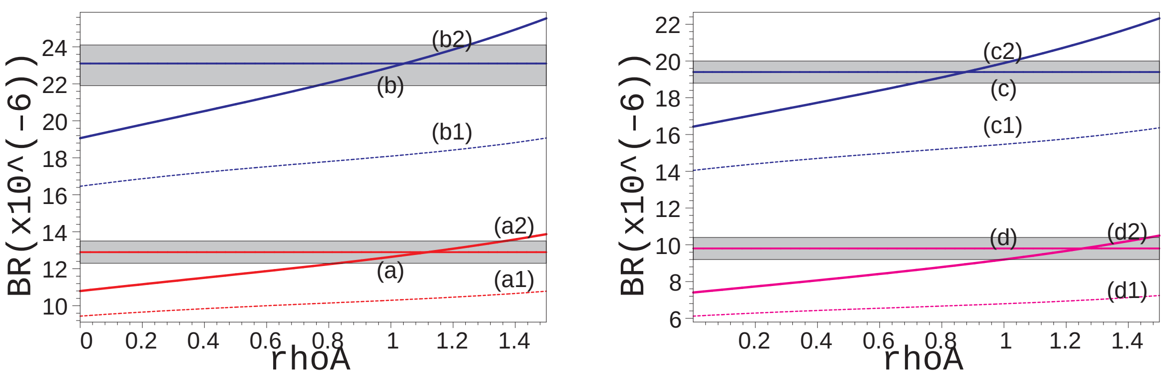

FIG. 2: The computed and measured CP-averaged branching ratios. The horizontal line are the measured values [1] with the gray areas represent the experimental errors. (a), (b), (c), (d) in the left and right figure represent the values for $B^- \to K^-\pi^0$, $B^- \to \bar{K}^0\pi^-$, $\bar{B}^0 \to K^-\pi^+$ and $\bar{B}^0 \to \bar{K}^0\pi^0$ respectively. The curves (a1)-(d1) and (a2)-(d2) are the corresponding QCDF predicted values for $\phi_A = -55°$, without and with additional penguin-like δP and color-suppressed δC contribution respectively.

Decay Modes	$\delta P = 0$ $\delta C = 0$	$\delta P \neq 0$ $\delta C \neq 0$	Exp [1]
$B^- \to \pi^-\pi^0$	5.7	5.7	5.59 ± 0.4
$B^- \to K^-\pi^0$	10.3	12.6	12.9 ± 0.6
$B^- \to \bar{K}^0\pi^-$	18.1	22.9	23.1 ± 1.0
$\bar{B}^0 \to K^-\pi^+$	15.5	19.9	19.4 ± 0.6
$\bar{B}^0 \to \bar{K}^0\pi^0$	6.8	9.2	9.8 ± 0.6

TABLE I: The CP-averaged $B \to K\pi$ Branching ratios in unit of 10^{-6} in QCDF with and without additional penguin-like δP and color-suppressed δC contribution and with $\rho_A = 1.0$, $\phi_A = -55°$

Decay Modes	$\delta P = 0$ $\delta C = 0$	$\delta P \neq 0$ $\delta C \neq 0$	Exp [1]
$B^- \to \pi^-\pi^0$	0.0	0.0	0.06 ± 0.05
$B^- \to K^-\pi^0$	0.01	0.06	0.05 ± 0.025
$B^- \to \bar{K}^0\pi^-$	0.004	0.01	-0.009 ± 0.025
$\bar{B}^0 \to K^-\pi^+$	-0.02	-0.08	$-0.098^{+0.012}_{-0.010}$
$\bar{B}^0 \to \bar{K}^0\pi^0$	-0.02	-0.11	-0.01 ± 0.10

TABLE II: The direct $B \to K\pi$ CP asymmetries in QCDF with and without additional penguin-like contribution δP and color-suppressed δC contribution and with $\rho_A = 1.0$, $\phi_A = -55°$

shows that QCDF could describe rather well the electroweak penguin contribution. We give here similar predictions with the additional color-suppressed term included (in unit of 10^{-6}):

$$\mathcal{B}(\bar{B}^0 \to \bar{K}^0\pi^0) = 9.3 \pm 0.3, \tag{27}$$

$$\mathcal{B}(B^- \to K^-\pi^0) = 12.4 \pm 0.3. \tag{28}$$

$$\mathcal{B}(\bar{B}^0 \to K^-\pi^+) = 20.1 \pm 0.6, \tag{29}$$

We see that because of the large color-suppressed contribution, the $\bar{B}^0 \to \bar{K}^0\pi^0$ predicted branching ratio is larger than the previous predicted value $(9.0\pm0.3)\times10^{-6}$ and is closer to experiment, the other two predicted branching ratios are almost unchanged and are in good agreement with experiment within the current accuracy.

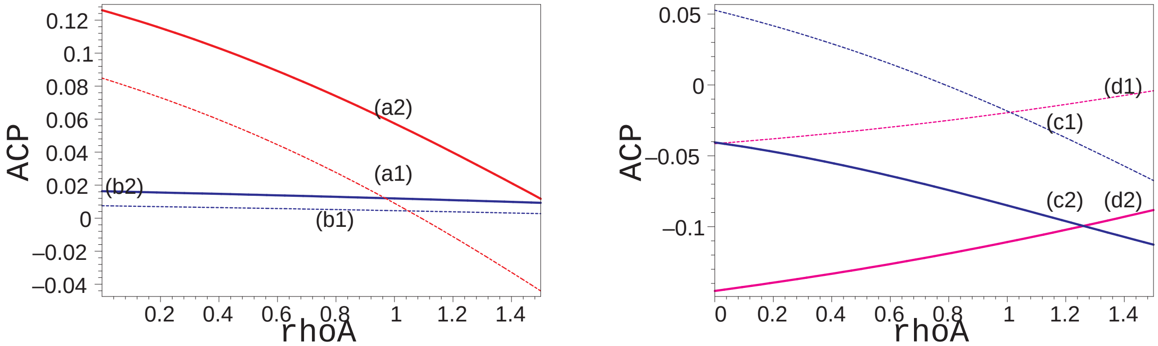

FIG. 3: The same as in Fig.2 but for the computed CP asymmetries.

IV. CONCLUSION

By adding mainly absorptive additional penguin-like and color-suppressed tree terms to the QCDF $B \to K\pi$ decay amplitudes, we show that QCDF could successfully predict the $B \to K\pi$ branching ratios and CP asymmetries. In particular, with a large negative strong phase for the color-suppressed tree contribution, we obtain the correct magnitude and sign for the $\bar{B}^0 \to K^-\pi^+$ and $B^- \to K^-\pi^0$ CP asymmetry, and a large negative asymmetry for $\bar{B}^0 \to \bar{K}^0\pi^0$. Confirmation of these CP asymmetries by new measurements and the measurement of $\bar{B}^0 \to \pi^0\pi^0$ CP asymmetry[24] would be an evidence for a large C/T ratio and a large strong phase in $B \to \pi\pi$ and $B \to K\pi$ decays.

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